

284

LIMITED CIRCULATION

This paper is not an official document: It is for information only and must not be quoted in any printed publication.

Agricultural Memorandum No. 1032

Carbon dioxide, climate change and UK agriculture

by N. Thompson

SUMMARY

Atmospheric CO₂ concentrations are likely to double before the end of the next century. Consequential climate changes will occur, although the consensus view of numerical modellers that a global temperature rise of several degrees will follow has been challenged, and has not been confirmed by comparing global temperature changes during the last fifty years or so with predictions based on the observed 15% increase of CO₂ in that period. Aside from any direct effects of CO₂ on climate, the increased crop yields and water-use efficiency which will follow from CO₂ increase are likely to have major effects on United Kingdom agriculture.

1. Carbon dioxide in the atmosphere

Anthropogenic production of carbon dioxide has been increasing for centuries, but during the last four decades the rate of increase has been rising sharply (Munn and Machta 1979): production is expected to continue upwards until well into the next century. Not all of the enormous quantities of CO₂ being released into the earth's atmosphere remain there; some is taken up at the earth's surface by plants, for example, and a substantial part is absorbed by the ocean. However, these sinks do not respond instantaneously to higher levels of CO₂ and so the atmospheric concentration is also increasing sharply at present. 1984 values are about 340 parts per million (ppm), an increase of around 50 ppm since the beginning of the century.

The processes controlling the uptake of CO₂ at the earth's surface have not yet been fully evaluated and this, coupled with uncertainties in the estimates of CO₂ prediction in the future, prevent precise specification of the levels of CO₂ in the next few score years. However, there is a consensus that concentrations will continue to rise through to the latter part of the next century, and that highest levels might exceed twice the present values. In the somewhat shorter term recent estimates by Goudriaan and Ketner (1984) set a likely range of CO₂ values in 50 years time between 100 and 150 ppm higher than at present.

FH2 B

2. Climate change and carbon dioxide

The major features of the earth's climatic fluctuations on very long time scales have been ascribed fairly convincingly to fluctuations in the intensity of solar radiation incident on the atmosphere caused by changes in eccentricity of the earth's orbit and in obliquity of its axis, and by precession, with periodicities of 97000, 40000 and 21000 years respectively (Milankovitch, 1930, 1938; Mason, 1976). At present it appears (eg Mitchell 1977) that the world is enjoying an interglacial period (period of high global temperature and relatively low ice cover), but that the expectation in the next 10000 years or so is for temperatures to begin to fall substantially: such astronomically-induced changes are relatively slow, however, and for example would be unlikely to lead to a mean temperature decrease of 1 degree C within the next 100 years.

Significant temperature changes on shorter time scales certainly occur, and have been ascribed to various causes such as sun-spot cycles and increases in vulcanicity.

It has long been suggested that changes in CO₂ concentrations in the atmosphere will cause climate changes through the so-called "greenhouse effect". The postulated mechanism follows from the low absorption coefficient of the gas for solar radiation, and high absorption for low-wave (terrestrial) radiation: thus an increase of CO₂ would be expected to lead to trapping within the earth's atmosphere of more of the incoming radiation, with a rise in temperature levels likely.

The response of the atmosphere to perturbations in its forcing function (such as its radiation balance) is very difficult to quantify because of the numerous interactions and feedbacks which take place. Much of the recent work on the effects of CO₂ change on climate has been carried out using global circulations models (GCMs) of the atmosphere. The models essentially solve simplified sets of dynamical and thermodynamical equations representing the important atmospheric processes: by repeating calculations using appropriately adjusted model radiation schemes it is possible to simulate the effects of altering atmospheric CO₂ levels. Examples of such simulations have been provided by Manabe et al (1981) and Mitchell (1983), and a review of a number of simulation studies has appeared in a 1982 report of the National Research Council of the USA. The majority of the models employed have broadly similar bases, and so, not surprisingly, agree generally in their main conclusion, which is that a doubling of CO₂ levels from 300 ppm (those during the early part of the present century) would lead to an average global temperature rise of around 2 deg C: the highest expected rises would occur in North Polar regions where they might exceed 5 deg C. Such changes in temperature, and related changes in rainfall, would have far-reaching consequences for agriculture.

It should be noted that cases have been presented for CO₂-induced climate changes very different from those deduced by the numerical modellers (eg Newell and Dopplick, 1979; Idso, 1982, 1984). Idso in particular has given arguments based on radiative properties of the atmosphere which suggest that CO₂-induced warming might be much less than the GCMs indicate, a view also given by Newell and Dopplick. Some support is provided by mean temperatures estimated from historical data by Hansen et al (1981). Since

1945, when atmospheric CO₂ concentrations began their sharp upturn, extratropical southern hemisphere temperatures have continued increasing slowly at a rate similar to that in earlier years, tropical area have had nearly constant temperatures following an earlier small increase, and extratropical northern latitudes have seen an overall slight cooling. This is in almost complete contrast to the results from GCMs which predict smallest increases in tropical regions and largest ones further north. The models' expectation of temperature rise due to the increase of CO₂ over the last few decades is about an order of magnitude less than that predicted to follow from a doubling of CO₂, and so would be barely detectable at present. Nonetheless, any evidence of actual temperature change is generally the opposite of that calculated by the models. This, coupled with the fact that these seemingly complex models still represent only very crudely, or not at all, many possibly important processes in the atmosphere, suggests that the case for a substantial temperature rise following expected CO₂ increases in the next 50 to 100 years, although strong, remains unproven. (It has been suggested that the apparent lack of response of the atmosphere to recent CO₂ increases may be because of the large thermal inertial of the oceans, which would feedback and therefore delay the atmospheric response: it may be significant that within the last decade there has been a small upturn of temperature in the Northern hemisphere, which could be interpreted as a phase-shifted consequence of CO₂ increase).

3. Carbon dioxide, plant growth and climate

Although it is not yet certain what will be the direct effects on climate of increasing atmospheric CO₂, it is definite that indirect effects will arise through the response of plants to CO₂. It has long been known that CO₂ directly influences growth: practical advantage is taken of this in horticulture where CO₂ enrichment of glasshouse atmospheres is widely used to increase the yield of crops such as tomatoes. The great majority of crops appear to respond in this way (eg Kimball, 1983), with a doubling of CO₂ leading to a yield increase of around one third. The largest response is shown by plants with the C₃ photosynthetic response; C₄ plants, such as maize, show generally smaller responses, but at present occupy a relatively minor position in UK agriculture: such large yield increases will clearly have a very large impact on agriculture, and may be welcome in all countries of the world if, by the time they occur, methods have been devised to distribute surpluses from areas like Northwest Europe to less advantaged nations.

What is likely to turn out to be at least as important as yield response is the effect of CO₂ on water-use efficiency. Stomatal aperture usually shows a dependence on CO₂ concentration, with aperture decreasing as concentration increases; a major effect therefore of CO₂ increases is to reduce the transpirational flow. Kimball (1983) deduced that on average a doubling of CO₂ would reduce plant water consumption by about one third, and so would roughly double the water-use efficiency.

These responses will lead to climate changes, aside from any caused by CO₂-induced changes in radiation balance, by allowing extension of cropping into areas of the world at present too arid to sustain growth at current

water use efficiencies. Cropped areas usually have lower albedos than bare soils and thus crop extension is likely to cause an increase in average global temperature (e.g. Idso, 1984).

4. Some possible consequences of CO₂ increase on UK agriculture

If the predictions of the GCMs turn out to be correct, then a doubling of CO₂ will cause temperature rises of several degrees over the UK; however corresponding rainfall changes over the same area have been predicted to be small (eg Manabe et al, 1981; Mitchell, 1983). Such a temperature rise would clearly cause a shift in the range of crops grown in the UK, and in particular would make the climate less favourable for producing high yields of small-grained cereals. This temperature increase would also increase evaporative demand (though plant water use would probably not increase, for reasons given above): atmospheric water vapour pressure would also be likely to rise, and thus reduce to some extent the increase in evaporative demand due to temperature rise alone. Appendix 1 discusses these last points further.

Aside from any direct CO₂ effects on climate, which as already indicated are still the subject of some debate, the influence of CO₂ on plant growth and water-use efficiency will have major consequences for UK agriculture. If meteorological factors remain the same, the likely at least one-third increase in crop yield which will follow a doubling of CO₂ would, in the absence of any substantial population increase, either lead to a reduction in the acreage cultivated or grazed, or provide greatly increased supplies for export; perhaps by the time such increases are achieved there will be a satisfactory financing system allowing distribution of these surpluses to less-favoured countries. Higher water-use efficiency will increase run-off, percolation and excess winter rain (eg Aston, 1984), and leaching of nutrients during the period of field capacity. Demand for irrigation water would be reduced, and the yields of many unirrigated crops further increased by a shortening of the period they would be likely to suffer stress from low soil moisture. Deleterious effects would include somewhat earlier return to, and later departure from, field capacity, and increase in the frequency of water-logging. There would certainly be changes in the patterns of pests and diseases: for example, the generally denser crop canopies and often wetter soil surfaces, would encourage a lengthening of the periods of high humidity which favour the development of many plant diseases.

It is possible to make detailed calculations of probable changes in, for example, irrigation water use, or crop yields in regions which at present frequently experience yield reductions caused by moisture stress. Such exercises would however be superficial and misleading because they neglect the various feedback processes (as yet not well understood) which are likely to be significant in controlling climate in the next 100 years. A number of these have been mentioned already, such as the direct influence of CO₂ on radiation balance, and changes in albedo (and radiation balance) following increased water-use efficiency and likely crop extension into semi-arid regions; other factors, such as changes in rainfall patterns, cloudiness, atmospheric water vapour and global wind fields will all have their effects, though by amounts which are not yet predictable. Further plant-related factors would include increase in surface (foliage)

temperature caused by the increase in sensible to latent heat flux ratio (Bowen ratio) that will result for well-watered plants, and changes in average stomatal response caused by any changes in average vapour pressure deficit. Because of all of these factors it is unprofitable to produce elaborate speculations based on detailed calculations which have to be supported in part at present by unproven hypotheses.

8. Conclusions

Evidence strongly supports a doubling of atmospheric CO₂ concentration before the end of the next century. Widely-divergent claims and counter-claims are being made on the probable effects of this continuing increase of CO₂ on future climate. The contention of numerical modellers in particular that a global warming of several degrees will follow from CO₂ doubling has not yet been confirmed by observations, even though CO₂ increases in the last four decades might, on the modellers' hypothesis, have been sufficient to cause a just-detectable temperature increase already: the lack of response might however be attributable to a delay in ocean warming due to its large thermal capacity.

In contrast, it is certain that a doubling of CO₂ will have a major effect on crop production, probably increasing yields by at least one third and doubling water-use efficiency, in the absence of major changes in climate. These effects will cause, inter alia, major changes in irrigation use, fertiliser consumption, and probably land utilization. It is worth noting that CO₂ increases within the last 50 years are likely to have already contributed at least a 5% increase to crop yields.

Any comments or queries on this paper should be referred to the author.

Meteorological Office Met O 8a
London Road
Bracknell
Berkshire
RG12 2SZ

October 1984

References

- Aston, A R (1984) The effect of doubling atmospheric CO₂ on streamflow: a simulation. *Journal of Hydrology*, 67, 273-280.
- Goudriaan, J and Ketner, P (1984) A simulation study for the global carbon cycle, including man's impact on the biosphere. *Climate Change*, 6, 167-192.
- Hansen, J, Johnson, D, Lucas, A, Lebedeff, S, Lee, P and Russell, G. (1981) Climate impact of increasing carbon dioxide. *Science*, 213, 957.
- Idso, S B (1982) Carbon dioxide: friend or foe? IBR Press, Tempe, Arizona, USA. 92 pp.
- Idso, S B (1984) What if increases in atmospheric CO₂ have an inverse greenhouse effect? I. Energy balance considerations related to surface albedo. *Journal of Climatology*, 4, 399-409.
- Kimball, B A (1983) Carbon dioxide and agricultural yield: an assemblage of 430 prior observations. *Agronomy Journal*, 75, 779-788.
- Manabe, S, Wetherald, R T and Stouffer, R J (1981) Summer dryness due to an increase of atmospheric CO₂ concentration. *Climate Change*, 3, 347-386.
- Mason, B J (1976) Towards the understanding and prediction of climate variations. *Quarterly Journal of the Royal Meteorological Society*, 102, 473-498.
- Monteith, J L (1965) Evaporation and environment. *Proc. Symp. Exp. Biol.* 19, 205-234.
- Milankovitch, M (1930) *Handbuch der Klimatologie I, Teil, A* (Ed. Koppen and Geiger), Berlin.
- Milankovitch, M (1938) *Handbuch der Geophysik*, Berlin, 9, 593.
- Mitchell, J F B (1983) The seasonal response of a general circulation model to changes in CO₂ and sea temperature. *Quarterly Journal of the Royal Meteorological Society*, 109, 113-152.
- Mitchell, J F M (1977) Carbon dioxide and future climate. Environmental Data Service, National Oceanic and Atmospheric Administration, US Department of Commerce.
- Munn, R E and Machta, L (1979) Human activities that affect climate. World Climate Conference, Geneva, (Feb, 1979), extended summaries of papers, WMO, 101-123.
- Newell, R E and Dopplick, T G (1979) Questions concerning the possible influence of atmospheric CO₂ on atmospheric warming. *Journal of Applied Meteorology*, 18, 822-825.

Thompson, N, Barrie, I A and Ayles, M (1982). The Meteorological Office
Rainfall and Evaporation Calculation System (MORECS). Hydrological
Memorandum No. 45.

Appendix 1 CHANGES IN POTENTIAL EVAPORATION CAUSED BY CO₂-INDUCED CHANGES IN SURFACE RESISTANCE AND TEMPERATURE

1. Present conditions

Assume that the surface is covered by a dense crop around 0.3m tall (surface roughness length $\approx$ 0.03m), and that meteorological conditions are as follows:

Wind speed at 10m (U)	4 m/s
Mean air temperature (T)	18 deg C
Mean vapour pressure deficit (δe)	8 mb
Mean available energy (R)	200 W/m ²
Rate of change of SVP with temperature (Δ)	1.3 mb/deg C.

Following Monteith (1965), the latent heat flux from the surface is

$$E = \frac{\Delta R + 1230 \delta e / r_a}{\Delta + 0.66 (1 + r_s / r_a)} \quad (1)$$

where the aerodynamic resistance r_s is approximately 190 /U s/m (e.g. Thompson et al, 1982) and the surface resistance r_s for a well-watered crop is about 40 s/m. Therefore, $E \approx 185$ W/m² (giving a daily transpirational loss of around 3.2 mm).

2. Conditions following a CO₂ doubling

In the absence of changes in any of the meteorological variables, the postulated CO₂ increase would reduce transpiration by around one third, so that $E \approx 123$ W/m². It may be deduced from equation (1) that the surface resistance has to increase to ~ 130 s/m to cause this reduction in transpiration. However, the likely increase in crop yield, which will follow the CO₂ increase, indicates a larger leaf area for the crop and so the new resistance has to be reduced (by a maximum of 25% for a yield increase of one third).

The results from GCMs generally support a warming of several degrees following a CO₂ doubling. If there is no change in vapour pressure this will cause δe to increase to 13.8 mb (if temperature rises by 4 deg C), and so from eq (1), with Δ now equal to 1.62 mb/deg C and r_s rising to around 100 s/m, the new value for E is 185 W/m². This is the same as the value calculated for conditions prior to the postulated CO₂ and temperature changes. Now, although the meteorological values chosen for the calculations in this Appendix are arbitrary, they are nonetheless fairly typical of summer conditions in the UK: it may be deduced therefore that even an increase in evaporative demand following from a several degree rise in temperature will only just compensate for the rise in surface resistance caused by a CO₂ doubling. Additionally, transpiration may be further decreased by an increase in mean vapour pressure which is likely to accompany the postulated rise in temperature. It may be deduced therefore that CO₂ doubling will not only increase crop yield and water-use efficiency, but will also decrease water consumption by the plants and so reduce irrigation needs.